Quarterly Progress Report

NASA/OSAT Submillimeter Sensor Technology Program

PERIOD: JANUARY - MARCH 1995

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NASA Office of Space Access and Technology (OSAT)
Submillimeter Sensor Technology Program

Long Term Program Goals and Objectives:

The objective of the OSAT Submillimeter Wave Sensors program is to develop components requiered for submillimeter wave heterodyne receiver systems and accurately characterize their performance. Performance requirements address the needs of NASA submillimeter space missions including the European Space Agency (ESA) Far Infrared and Submillimeter Space Telescope (FIRST) and the earth remote sensing EOS Microwave Limb Sounder (EOS MLS). Performance goals include extending technical capability to higher frequencies (1200 GHz in the near-term, 3000 GHz in the far-term), improving sensitivity an order of magnitude, and developing a viable array technology. JPL, in collaboration with other organizations, Caltech, Yale, MIT, U. of Virginia, U. Mass, MIT-Lincoln Lab, TRW, UCSB, and Georgia Tech., is developing submillimeter heterodyne technologies which will enable future submillimeter astrophysics missions.

The NASA/OSAT submillimeter Sensor Technology Program supports the following two missions:

A. Astrophysics

B. Earth Remote Sensing

A. Submillimeter Wave - Astrophysics

A. Submillimeter Wave - Astrophysics

A 1. Introduction

The emission in the electronmagnetic spectrumn between 30 and 1000 μm, the far-infrared and submillimeter wave band, arises primarily from relatively cool, diffuse media such as interstellar and circumstellar dust and gas. Black-bodies with temperatures between 5 and 50 K peak in this range, and gases with temperatures between 5 and a few hundred K emit their brightest molecular and atomic emission lines in this wavelength range. Low temperatures are characteristic of a significant fraction of the visible mass in the Universe, including dense interstellar clouds and embedded protostellar condesations, planets, comets, outer atmospheres of evolved cool stars, and nuclei of active galaxies. JPL, in collaboration with other organizations, Caltech, Yale, MIT, U. of Virginia, U. Mass, MIT-Lincoln Lab, TRW, UCSB, and Georgia Tech., is developing submillimeter heterodyne technologies which will enable future submillimeter astrophysics missions. These missions will make key contributions to answer fundamental questions of modern astrophysics, including:

- the formation and early physical and chemical evolution of stars and the related issue of the formation and physical and chemical evolution of disks and planets around embryonic stars
- the origin of young solar systems
- the nature of the luminous infrared galaxies discovered by IRAS and the question of whether quasars and star-burst galaxies are related by evolution, and more generally the role of star-burst phenomena in the evolution of galaxies
- the question of when and how galaxies formed in the early universe

A. 2 Objectives

The objective of the OSAT Submillimeter Wave Sensors program is to develop space qualifiable components required for submillimeter wave heterodyne receiver systems and accurately characterize their performance. Performance requirements address the needs of NASA submillimeter missions. Performance goals include extending technical capability to higher frequencies (1200 GHz in the near term, 3000 GHz in the far-term), improving sensitivity and order of magnitude and developing a viable array technology. Near-term objectives include demonstration of receivers near 600, 800 and 1200 GHz. Longer-term objectives include receivers to 3000 GHz and receiver arrays for astrophysical applications.

A. 3 Work Breakdown Structure (See Figure 1 for road Map)

1. Mixer Develoment

1.1 SIS Tunnel Junctions (JPL)
1.2 Hot Electron Bolometer (Yale, JPL, Caltech)
1.3 Quantum Wells (MIT)

2. Local Oscillator

2.1 Mulipliers (JPL, UVa, Michigan, U. Mass.)
2.2 Photomixer (MIT-Lincoln Lab)
2.3 Grids Multipliers (Caltech)

3. Receiver Development

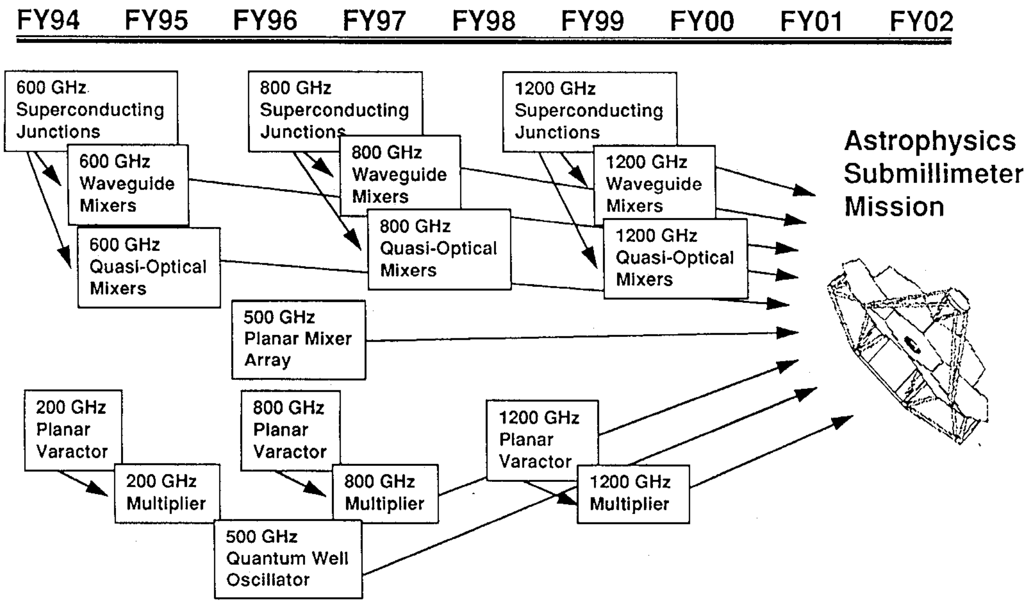
3.1 Quasi Optical (Caltech)
3.2 Wave Guide (JPL)

4. Backend Electronics

4.1 Digital Autocoorellator Spectrometers (JPL, Caltech)
4.2 HEMTS (TRW, UCSB, U. of Hawaii, JPL)

5. Array Development (JPL, Caltech)

ASTROPHYSICS SUBMILLIMETER SENSORS ROADMAP



Technical Progress

1.0 Mixer Development

1.1 Superconducting Mixer Elements for Submillimeterwave Receivers

PI: **H. LeDuc**
Collaborators:

Objective:
The object of this task is to develop mixer elements fabricated from refractory superconductrors such as Niobium and Niobium Nitride. The base line devices for these mixer elements are Superconductor-Insulator-Superconductor (SIS) tunnel junctions. For frequencies upto 720GHz (gap frequency of Nb), Niobium based SIS mixers have unequaled performance. For higher frequencies Niobium Nitride based SIS mixers are being developed. In addition, two other approaches are being explored. The first is hybrid mixers based on Niobium SIS tunnel junctions and either normal metal or larger gap superconductor tuning structures. The second is based on electron diffusion cooled hot electron bolometers. If successful these devices would be used on SOFIA, and SMIM/ FIRST.

Progress:

1. The fabrication NbN mixers for 547/630: Devices have been fabricated and delivered for RF-testing. No results have been reported.

2. $Nb/AlO_X/Nb$ tunnel junctions integrated with twin slot antennas for 500 and 650 GHz operation have been fabricated and delivered to Caltech. The mixers have been tested on CIT's Fourier Transform Spectrometer (FTS) to test tuned bandwidth and center frequency. RF performance has been measured for the highest frequency band. The receiver noise temperature is 800 K at 800 GHz which <u>is the lowest noise temperature reported at this frequency</u>. Since this is above the gap frequency of Nb (720 GHz) losses in the superconducting tuning circuits are expected to negatively impact device performance. This was confirmed indirectly by lowering the devices temperature from 4.2 K to 2.5K which should reduce rf-losses. The receiver noise was reduced to 625K at 800 GHz under these conditions.

3. The fabrication process for diffusion cooled hot electron bolometers has been improved.

    <u>Background:</u> A potential problem with fabrication of submicron dimension microbolometers is the configurational tradeoffs imposed by layer-to-layer alignment tolerances inherent in the electron beam lithography process. (The experimentally determined layer-to-layer alignment tolerances are 0.2 mm in this process. This is quite good, however , since the hot electron bolometers have dimensions on the same order it is not quite good enough.)

   <u>Improvements:</u> A self aligned fabrication process has been developed which eliminates the potential limiting device geometries by forming the alignment critical

device layer using an etch mask composed of two lithographic steps combined together.

Planned for Next Quarter:

1. Fabricate NbN/NgO/NbN 630 GHz mixers for the JPL waveguide mixer task.

2. Continue development of hybrid junction/tunner technology

1.2 Hot Electron Bolometer Mixers

PI: **W. McGrath**
Collaborators: **A. Skalare, B. Bumble, H. LeDuc - JPL**
D. Prober, P. Burke, A. Verheijen - Yale University
J. Zmuidzinas - Caltech

Objective:

The objective of this task is to fabricate, measure, and optimize the heterodyne mixer performance of a novel diffusion-cooled, hot-electron, transition-edge bolometer mixer. This is a unique bolometer which is both sensitive and fast: IF's up to 4 GHz and near quantum-limited noise performance are predicted for rf frequencies up to at least 10 THz. The current goal is to measure the noise temperature, conversion efficiency, IF bandwidth, and LO power level of a submicron Nb bolometer at 530 GHz. This sensor is being developed for low-background submillimeter and far-infrared missions such as SOFIA and FIRST as well as ground and balloon-based observatories.

Progress:

- A wide-band, 0.5-18 GHz IF amplifier was purchased and installed in the 530 GHz receiver on the 77 K stage. A special, wide-band cryogenic bias-tee was designed, fabricated, and tested. Due to parasitics, the resultant useful bandwidth of the modified IF system is 0.5-5 GHz. This is sufficient to measure the IF rolloff frequency of the bolometer mixer.

- A unique approach using a broadband, blackbody rf source and a spectrum analyzer as a tunable, narrow bandpass filter in the IF system was employed to accurately measure the IF rolloff of the bolometer mixer. The rolloff was measured to be 1.7 GHz (and up to 1.9 GHz for slightly lower conversion efficiency). This is close to the expected value for reasonable self-heating in the device. This is the **fastest** bolometer mixer ever developed.

- A new theoretical analysis of the bolometer mixer operation based on a finite-difference approach is being developed. This theory is less model-dependent that current theories being published and should allow us to explore the high frequency performance of this unqiue mixer.

- The LO power has been estimated from the self-heating correction fitted to the IF rolloff frequency. The value is less than 16 nW. This is close to the expected value, and of course is very low which is desirable for a submillimeter wave mixer where LO power is difficult to come by.

- Initial designs of 1200 GHz planar double-dipole antennas have been done. Double-slot antennas are now being considered. The basic layout for a microfabrication mask set being developed. The laser LO coolant system and power supply have been setup.

- Circuit designs for 10 GHz and 100 GHz have also been done for low frequency tests to be performed at Yale. Peter Burke and Robert Schoelkopf from Yale visited my lab during the week of March 20-24.

Planned for Next Quarter:

- Write-up and submit for publication the current results on the 530 GHz hot-electron bolometer mixer.
- Continue analysis of mixer results with new theory.
- Install required safety system for laser LO system, for 1200 GHz mixer.
- Finalize the 1200 GHz bolometer mask design.

1.3 Terahertz Detectors And Mixers Using Quantum-Well Structures

PI: Qing Hu (MIT)

Collaborators: Mike Melloch (Purdue University)

Objective:

The goal of this project is to develop alternative detection and mixing elements other than SIS tunnel junctions for applications at frequency at and above one Terahertz. Nb-based SIS mixers are limited to the superconducting gap frequency of 750 GHz, because the superconducting electrodes become very lossy above this gap frequency. Furthermore, even if SIS junctions with higher-gap materials, such as NbN, can be made, they will still be limited by their RC time constant. For tunnel junctions, the RC time constant is determined by, $\tau = RC \sim \exp(E^{1/2}d)/d$, where E and d are the height and thickness of the tunnel barriers, respectively. For SIS junctions using oxidized aluminum as tunnel barriers ($E \approx 10$ eV), this time constant corresponds to a frequency less than one Terahertz. The main reason that the time constant is so long is that the barrier height is too great. A barrier height of 10 kT is sufficient in order to suppress thermionic over-the-barrier emissions. At cryogenic temperatures, this barrier height can be as low as 10 meV (corresponding to 120 K). It is in this spirit that we are seeking different tunnel structures whose barrier heights are much lower than that of oxidized aluminum.

Semiconductor MBE-grown quantum-well structures have barrier heights typically in the range of 100 meV, which is two orders of magnitude lower than that of SIS. Semiconductor laterally confined quantum-well structures have barriers tunable by the gate voltages, and their heights can be as low as several meV. Naturally, both structures are attractive candidates for ultrahigh-frequency (>1 THz) applications.

Progress:

We have performed an extensive study on photon-assisted transport/tunneling in lateral quantum-effect devices with one and two barriers. Aided by a simulation study that numerically solves time-dependent Schroedinger equation, we realized that photon excitation in a one-barrier device requires a spatial localization of the photon field to provide the momentum transfer. This can be achieved by placing the antenna terminals very close together (approximately 0.2 microns). In double-barrier devices, however, this momentum transfer can be provided by the quasibound electronic states. This photon-assisted transport in double-barrier devices has recently been observed in our group.

Future plans:

We plan to fabricate lateral quantum-effect devices with single barriers. These devices will be coupled to antennas with closely spaced terminals to provide a localized photon field near the barriers. We plan to study photon-assisted transport in these devices. We also plan to study photon-assisted tunneling in coupled double quantum-well structures grown by MBE.

2.0 Local Oscillator

2.1 Local Oscillators: Multipliers

PI: **Dr. Peter H. Siegel, JPL**
Collaborators: **Dr. Tom W. Crowe - University of Virginia Semiconductor Device Laboratory**
Dr. Neal Erickson - University of Massachusetts
Professor Jack East - University of Michigan

Purpose:

To develop broad band, low power, solid-state, planar-diode- multiplier based local oscillator sources from 400-1200 GHz for submillimeter-wave heterodyne radiometry of astrophysical sources. This technology is essential for enabling the receiver deployment planned for FIRST/SMIM and represents the baseline approach for meeting the science needs for that instrument. It also represents an opportunity for the successful deployment of new enabling technology developed under the OACT program, in this case the broad band planar diode multipliers, which replace the less reliable, much narrower band whisker-contact diode-multiplier technology found in today's submillimeter wave receivers.

Progress:

JPL: Complete workforce now in place. Initial design for planar diode multiplier from 160-640 GHz underway using, for the first time, double stage multiplication in a single waveguide block. Analysis of circuit using HP Microwave Design System, GISSMULT and Libra cross-compared with excellent agreement. Custom in-house developed Finite Difference Time Domain analysis for complete frequency domain characterization also being utilized to develop new multiplier filter structures. Design of novel open-structure multiplier circuit for 600-1200 GHz begun. Initial design will focus on single planar-varactor-diode in quasi-optical mount. Varactor diode wafers ordered. Device design for submillimeter operation begun.

UMass: Initial design for novel broad-band planar varactor tripler using self-biased diodes completed. Translation to device masks to begin next quarter. Second round of measurements on high-power 80-160 GHz doubler completed. Record breaking 40% conversion efficiency with 50mW output power obtained. First tests of 160-320 GHz high power doubler completed. 5mW output power obtained at 320 GHz. Second batch of diodes in process. First 810 GHz whisker-contacted waveguide tripler tests completed. 100 microwatts output power obtained over 10% bandwidth with peak power of 150 microwatts. 1200 GHz tripler now planned for demonstration before end of 1995.

UVa: Second batch of planar diode series arrayed balanced multiplier chips completed and delivered to UMass. Second batch of 160-320 GHz balanced diodes almost completed. 810 GHz whisker contact multiplier diodes completed and delivered to UMass. 200 GHz single planar varactor diode chips completed and delivered to JPL.

UMich: Monte Carlo analysis of high frequency varactor diodes completed. GaAs based device limitations at high frequencies identified. Design of InP based devices begun.

Planned for Next Quarter:

JPL:
Complete design and begin analysis/modeling of 160-640 multiplier.

Complete design and begin analysis/modeling of 600-1200 GHz open-structure multiplier.
Begin fabrication of self-biased varactor diode for evaluation.
Test UVa planar varactor chips in existing 200 GHz doubler and tripler mounts.

UMass:
Begin design of 1200 GHz waveguide tripler.
Test 160-320 GHz doubler with new diode chips.
Complete design of self-biased tripler.

UVa :
Deliver 160-320 GHz diodes to UMass.
Complete sample run of self-biased tripler devices.

UMich:
Begin design/fab. of InP based varactor chips.
Continue analysis of high frequency device performance.

FY 95 Milestones	O	N	D	J	F	M	A	M	J	J	A	S
Completed 160-640 GHz dual-doubler												**X**
Completed 600-1200 GHz open-struct. mult.												**X**
Completed self-biased tripler												**X**
Completed 1200 GHz waveguide tripler												**X**
Analysis results						**X**			**X**			**X**
Completed planar diodes		**X**			**X**			**X**		**X**		**X**

2.2 Terahertz Tunable Photomixer Local Oscillator for Astrophysics

PI: E. R. Brown (MIT Lincoln Laboratory)

Collaborators: Rob McGrath (JPL), and Prof. Kerry Vahala (Caltech)

Objective: The goal of this program is to develop a coherent local-oscillator source with output power of at least 10 μW and continuous tunability from about 500 GHz to 1.2 THz. The basis for the source is a low-temperature-grown (LTG) GaAs photomixer pumped by two, frequency-offset diode lasers.

Progress:

Since the last report approximately one quarter ago, a terahertz photomixer source has been constructed completely from solid-state components and has been demonstrated with continuous tunability over the frequency range from 100 GHz to 1.5 THz. The block diagram of this source is shown in Fig. 1. The photomixer is the same one developed in the previous quarter. It consists of an 8x8-micron active area of interdigitated electrodes defined directly on a 1.5-micron-thick epitaxial layer of low-temperature-grown GaAs. The active area is mounted at the center of a three-turn self-complementary spiral antenna. The GaAs chip containing the photomixer is mounted on the back side of a high-resistivity silicon hyperhemispherical lens. The combination of spiral antenna and lens emits a Gaussian beam into free space having a beam width of roughly 10 degrees (at the 10-dB-down points) and a circular polarization.

The key improvement in the photomixer source of Fig. 1 is the presence of two commercial diode-laser pumps. Both lasers contain distributed Bragg reflectors (DBRs) to achieve single-frequency operation over the entire tuning range of approximately 1.5 THz. The tuning is carried out by changing the laser operating temperature using a miniature thermoelectric cooler. One laser is designed for a room-temperature operating wavelength of 850 nm, and the other is designed for a wavelength of 852 nm. The output power of the 8x8 micron photomixer over the 0.1-to-1.5 THz range is shown in Fig. 2 in comparison to the output of the same photomixer obtained with table-top titanium:sapphire pumps. The output spectra are practically identical, demonstrating that the optical mixing efficiency and optoelectronic conversion efficiency are the same with the two different pumping techniques. The 3-dB bandwidth of the diode-laser spectrum is approximately 900 GHz, which is the highest bandwidth ever measured for an LTG-GaAs photomixer. The absolute power in Fig. 2 was measured at Lincoln Laboratory with a silicon composite bolometer. At the low-frequency end, the power was found to be approximately 10 microwatt.

During the week of March 13, the photomixer breadboard of Fig. 1 was delivered to Caltech and JPL for system tests. At Caltech, the output spectrum was measured with an InSb hot-electron bolometer, and the absolute power spectrum was determined to be nearly identical to that measured at Lincoln Laboratory. In addition, the photomixer output was coupled for the first time into a superconductor-insulator-superconductor (SIS) receiver (designed by Jonas Zmuidzinas). The optical coupling was tricky, as expected, because of the single antenna modes of both the photomixer and SIS mixer. Unfortunately, mixing experiments were not conducted owing to a failure of the cold HEMT amplifiers in the SIS cryostat. Following the Caltech experiments, the photomixer breadboard was delivered to Rob McGrath's laboratory at JPL. The first experiment at JPL will couple the photomixer output to McGrath's 600-GHz superconducting hot-electron-bolometer receiver and will be conducted during the next quarter.

Plans for Next Quarter:

- Conduct experiment to couple the photomixer output into the 600-GHz superconducting hot-electron bolometer receiver at JPL. This experiment is scheduled to start April 15, 1995.
- Characterize the instantaneous linewidth using the photomixer as the input signal near 600 GHz, and measure the receiver noise temperature using the photomixer as the local oscillator.

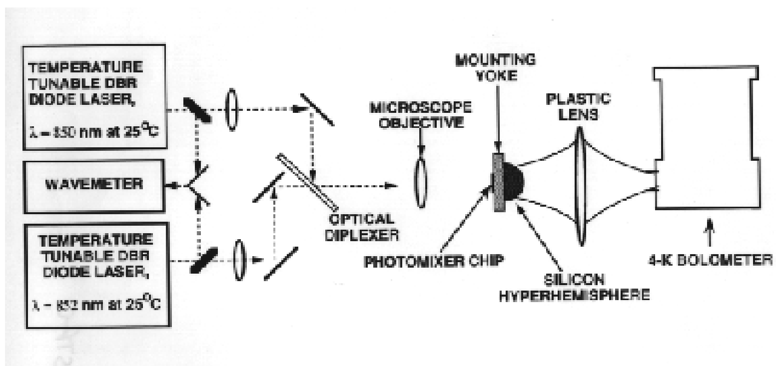


Fig. 1. Experimental block diagram of all-solid-state terahertz source consisting of an LTG- GaAs photomixer coupled to a three-turn log-spiral antenna. The output power at the low-frequency end is approximately 10 mirowatts.

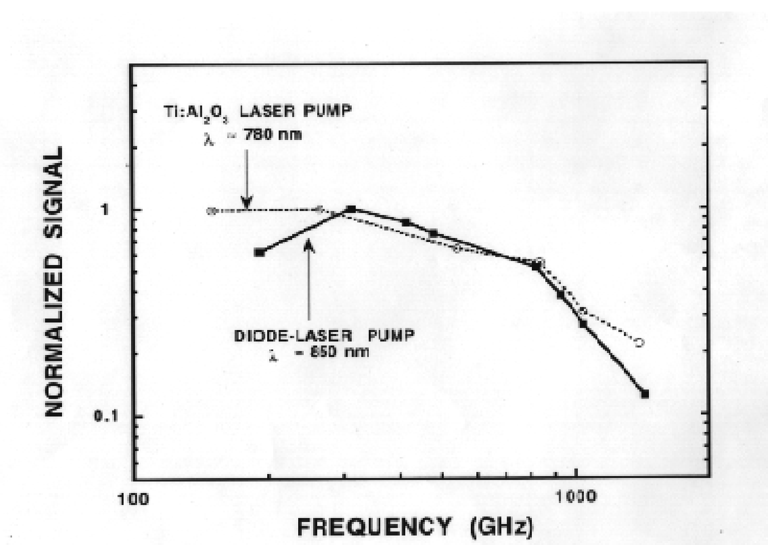


Fig. 2. Output power of all-solid-state terahertz source using two DBR diode lasers as optical pumps, one having a room-temperature wavelength of 850 nm and the other having a wavelength of 852 nm.

2.3 Submillimeter-wave Grid Multipliers

P.I.: Professor David Rutledge (California Institute of Technology)

Objective

We propose to design, build and test grid multipliers to operate at submillimeter wavelengths as local oscillators for space-borne focal-plane integrated-circuit antenna arrays. The goal of this project is to provide local oscillators for the Astrophysics Submillimeter Mission project managed by Dr. William Gray at Jet Propulsion Laboratory. This mission requires a local oscillator for the heterodyne receiver with a tuning bandwidth bigger than 10 %, and an output power bigger than 50 μ W at 1 THz. The design of our grid multipliers is suitable to meet the requirements at THz ranges. The goals of our grid multipliers also meet the needs of the EOS Microwave Limb Sounder project managed by Dr. Gary Lau at Jet Propulsion Laboratory.Their needs include local oscillators for a 2.5\ts THz radiometer.Our grids would provide a 1.25 THz local oscillator for a subharmonic mixer.

A pulsed THz quasi-optical grid frequency doubler has been developed. This frequency doubler is a planar bow-tie grid structure periodically loaded with planar Schottky diodes.This is the first experimental result with quasi-optical grid frequency multipliers at terahertz frequency ranges.A peak output power of 330 μW was measured at 1 THz with a peak inputpower of 3.3 W at 500 GHz without any impedance tuning.

Background

Submillimeter-wave local oscillators for space-borne receivers and focal-plane arrays present severe technical challenges. Power levels in the range from1 mW to 100 mW are needed. This is quite difficult, even in a laboratory on the ground. NASA has considered launching submillimeter gas lasers, but these are large, and often require aCO_2 pump laser with a high-voltage power supply. Vacuum tubes are a possibility, but there are severe reliability problems, and the weight and size required by the magnets and power supply can be very large. From the perspective of size, weight, reliability, and power consumption, a solid-state source would be greatly preferable. Frequency multipliers and upconverters like Schottky diode multipliers can be used to generate the required terahertz frequencies from lower-frequency solid-state tunable signal sources such as Gunn diode oscillators.

Current diode multipliers have mostly been single-diode structures typically consisting of a Schottky varactor diode placed in a waveguide with a whisker contact. At present, the power outputs from waveguide multipliers that are commercially available from Neal Erickson at Millitech are between 100 μ W and 1 mW at 600 GHz. Rydberg, Lyons and Lidholm have demonstrated a Schottky varactor diode frequency tripler with a measured output power more than 120 mW at 803 GHz. P. Zimmermann has demonstrated a measured output power of 60 μW at 1 THz by using a cascade of two whisker contacted Schottkyvaractor frequency triplers.

One approach to overcome the low-power limit inherent with solid-state devices operating in the submillimeter-wave band is to efficiently combine a large number of devices together. A grid of planar diodes quasi--optically coupled in free space does not require the construction of single--mode waveguides and can potentially overcome the power limit of conventional single--diode multipliers. Using this approach, H.-X. Liu has demonstrated a pulsed 99\ts GHz frequency tripler consisting of 3100 Schottky-quantum-barrier varactor diodes that produced 5 W at 99 GHz.

The University of Virginia has built planar diodes with excellent performance at submillimeter wavelengths. In addition, Caltech has been developing diode grids for high-power mixing, multiplication and phase shifting. One advantage of the grid approach is that the output power scales with the area. To increase the power, we simply increase the area. Another potential advantage is great reliability. Our experience has been that diode failurerates in the grid can be as large as 20 % without significantly hurting performance.Therefore we propose to extend the grid power-combining works to higher frequencies to provide a solid-state local oscillator for a focal-plane array.

Approach

The multiplier configuration is shown in figure 1. The input beam at the fundamental frequency enters from the left. The first element is a pair of dielectric tuning slabs that act to transform the impedance of the input wave to one appropriate for the multiplier grid. Typically inductive reactance is needed to cancel capacitance of the varactor diodes in the grid. In addition, the free-space wave impedance, 377 Ω, is inconveniently high and needs to be reduced. Next the beam passes through a Fabry-Perot resonator that is tuned to pass the fundamental frequency, but reflect harmonics. Then the beam hits the grid. The grid acts a non-linear capacitance, and generates harmonics. This harmonic beam radiates both forward and backward, but the backward beam reflects off the Fabry-Perot resonator. The forward beam passes through the high-pass filter, and then through another pair of tuning slabs. One important feature is that the tuning slabs are outside the filters, so that the input and output can be tuned independently.

The entire structure is quite compact, only a few wavelengths thick. The design is also suitable for cascading, so that even higher harmonics of fundamental could be produced. The multiplication process preserves the beam shape, and a focussed beam could be used so that different sizes of multiplier grids could be cascaded.

Progress:

A pulsed THz quasi-optical grid frequency doubler has been developed.This frequency doubler is a planar bow-tie grid structure periodically loaded with planar Schottky diodes.This is the first experimental result with quasi-optical grid frequencymultipliers at Terahertz frequency range.A peak output power of 330 microwatts was measured at 1 THz with an input power of3.3 watts at 500 GHz without any impedance tuning.

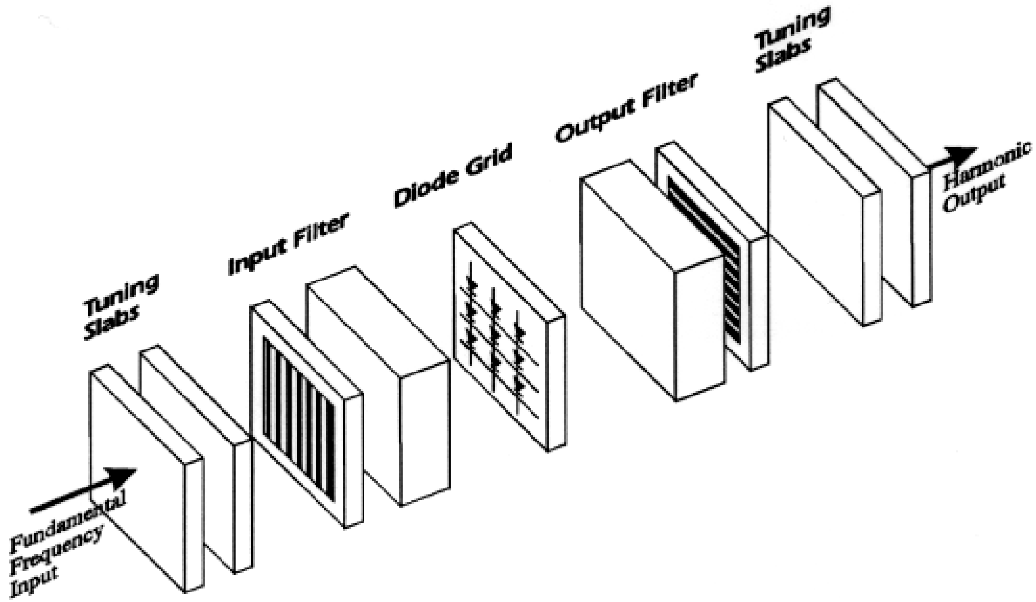


Fig. 1: Grid multiplier. The fundamental wave enters on the left as a beam, passes through a filter, and is incident on the multiplier grid. The grid acts as a non-linear capacitance and produces a beam at the harmonic frequency, which passes through filters on the right.

Several 6x6 Schottky diode grids have been fabricated by the Universityof Virginia. We received these diode grids in August.These diode grids are originally designed for sideband generators, butwe used them as multipliers to demonstrate the feasibility.These diode grids were fabricated on 25microns thick quartz substrates witha relative dielectric constant of 3.78.Figure 2(a) shows the bow-tie-shaped metalpattern used for the unit cell.The Schottky diode junction was placed at thecenter of the unit cell and two 7-microns fingers connected the anode andcathode of the diode to the bow-ties.The diameter of the anode is 0.5microns.The diode has an average measured DC series resistance of 14 ohms and an estimated junction capacitance of 0.4 fF at zero bias.Figure 2(b) shows the whole 6x6 array.The active frequency--multiplication area is 420x420 μm^2. The polarity of the diodes is flipped above andbelow the center row to allow dc bias which is fed to the center horizontalrow and the top and bottom edges.The change of polarity is for the original design of the sideband generators.This will cause an undesired null in the far field pattern for multiplierapplications.However, the purpose of this work is to utilize thenonlinearity of the diode grid to demonstrate the feasibility of frequency multiplication at THz ranges.

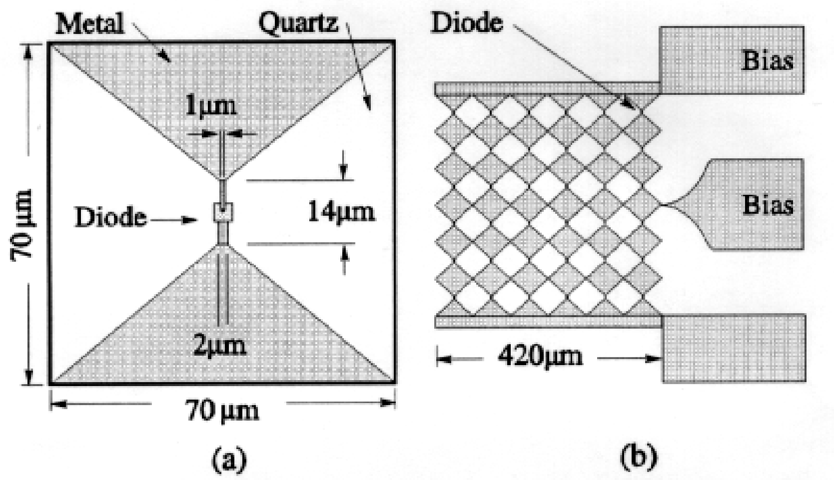


Fig. 2: The grid frequency doubler. (a): the unit cell, (b): the whole 6×6 array.

Measurements have been done by using a free electron laser as input source.The pulse rate is 0.75 Hz and has a pulse width of 2.42 µseconds. An 8--layer mesh filter and a waveguide filter were used as a low pass filter inthe input side and a high pass filter in the output side, respectively.A helium-cooled germanium detector was used to measure the output power ofthe second harmonic signal and a pyroelectric detector was used to measure theinput power of the fundamental frequency signal. Figure 3 shows the measured signal in time domain.The bolometer response isslower than the pulse width so the output voltage from the bolometer is relatedto the energy of the second harmonic pulse from the grid.Comparing the solid line and the dashed line,this measurement verifies thehigher harmonic signal comes from the multiplierbut not the leakage of the free electron laser.

A Fabry-Perot interferometer with a spacing accuracy of 0.7 microns was used to verify the signal frequencies (Fig. 4).The input frequency was measured without the grid and the high pass filter.The output frequency was measured by placing the Fabry-Perot interferometerbetween the grid and the high pass filter.The input frequency is 500 GHz and the output frequency is 1 THz.

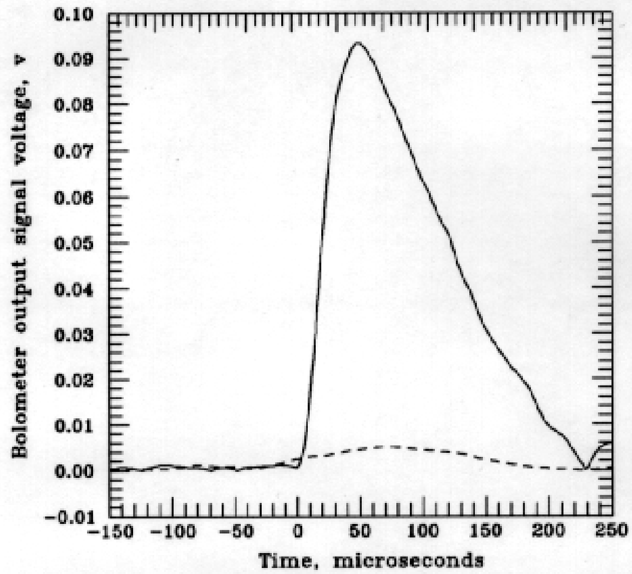


Fig. 3: Measured output pulses. The solid line was measured with the grid multiplier in the path and the dashed line was measured without the grid multiplier.

Figure 5 shows the power dependence of the multiplier #1 with normal incidence. This diode grid has diodes with an anode diameter of 0.56 µm and 100% yield. The dashed line indicates a square-power law. A peak output power of 330 µW at 1 THz was achieved when the diode grid was pumped with an input power of 3.3 W at 500 GHz. It should be noticed that these diodes have not been saturated yet in our measurement.

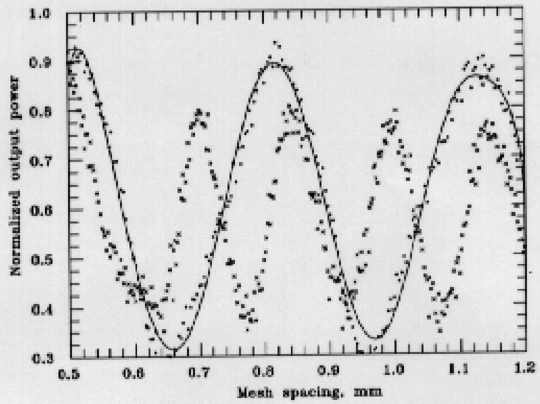


Fig. 4: Frequency verification by using a Fabry-Perot interferometer. The solid line and • indicate input signal and × indicates output signal.

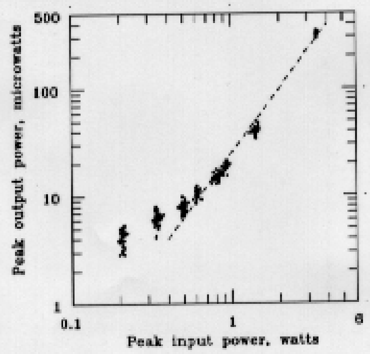


Fig. 5: Measured peak power dependence of the multiplier #1.

Data acquisition arrangement was changed to reduce the effect of noise in order to investigate the power dependence with low fundamental input power. Figure 6 shows the power dependence of the multiplier #2 with normal incidence. This diode grid has diodes with an anode diameter of 0.5 μm and 100 % yield. The solid line indicates a square-power law fit. With an input power of 0.8 W, the multiplier #2 generated an average peak second harmonic power of 45 μ mW. Again, these diodes were not saturated yet in these measurements either.

Output pattern was measured to verify the existence of the null in the center of the far field pattern (Fig. 7). Peaks appear at about 30° from the center and have 3\ts dB more power than in the null. This measurement verifies our assumption on the relationship between the polarity of the diodes and the output pattern. At least 80 % of the second harmonic signal power was wasted due to this wrong pattern.

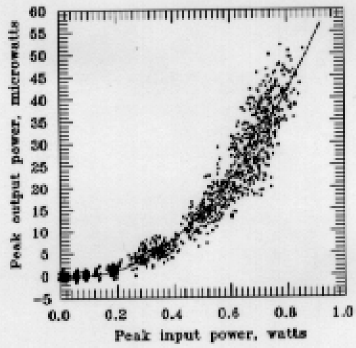


Fig. 6: Measured peak power dependence of the multiplier #2.

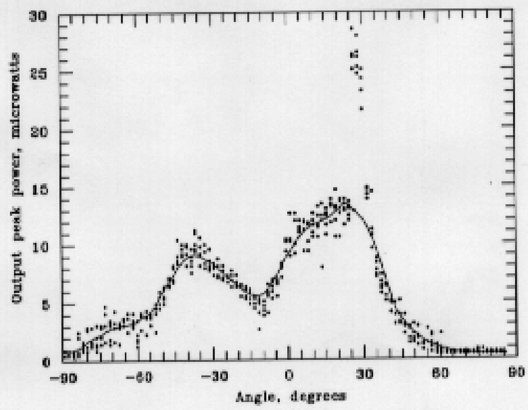


Fig. 7: Measured output pattern.

In most of the cases, Schottky diode multipliers were reverse-biased to increase the frequency multiplying efficiency since the diodes were designed as varactors. However, these diodes were originally planned for use as sideband generators and designed to be used under forward bias. Thus, these diodes have very thin epitaxial layers and the capacitance does not change significantly with reverse bias. Therefore, the frequency multiplication in these diode grids possibly came from varistor multiplication, that is to say, from the nonlinear I-V relationship. C-V curves have been measured by probing each diode in an array when other diodes were still connected with the one probed. The RF frequency is 1 MHz. The average capacitance of the diodes on the edge of the array stay the same (about 10 fF) when the bias changed from 0.4\V/ to -6V. The average capacitance of the diodes in the center of the array varies from 19.2fF to 18.4 fF as the bias changed from 0.4V to -6V. These capacitances were much bigger than the estimated junction capacitance which is 0.4 fF. The discrepancy is due to the fact that these diodes were still connected and therefore the measured capacitance is a result of all shunt capacitance in the array and the varactive capacitance was not significant to change it when the bias changed.

The grid was rotated by about 30° to receive the radiation from the maximum of the output pattern. The peak of the output pattern should be more sensitive to the bias conditions than the null in the center (with normal incidence) due to the fact that the null was caused by cancellation of Ê fields from the opposite polarities of the diodes.

Power dependence was also measured under different biasing conditions on the multiplier #2. Figure 8 shows the measured peak power dependence of the multiplier (a) with bias 0 V and 0.5 V; and (b) with bias 0.136 V and 0.665 V. Each data point is an average of 60 pulses. The frequency doubling efficiency at 14\uW/ output power was increased from 0.0015% with zero bias to 0.0039% with 0.5 V bias The frequency doubling efficiency at 14\uW/ output power was increased from 0.0013\% with 0.136 V bias to 0.004% with 0.665 V bias. The power saturation was also observed when the diodes were biased at zero bias and 0.136 V.

The peak output power contour as a function of peak input power with different biases from -0.07 V to 0.79 V was measured and shown in figure 9. Each data point is an average of 30 pulses. The frequency doubling efficiency was significantly increased as the bias changed from 0.2 V to 0.3 V. The peak output power with the biasing line open is about 13 μW (an average of 40 pulses). It seems not very helpful to increase the second harmonic generation by applying bias across the diodes. One possible reason is that these diodes were self-biased when the bias lines were open.

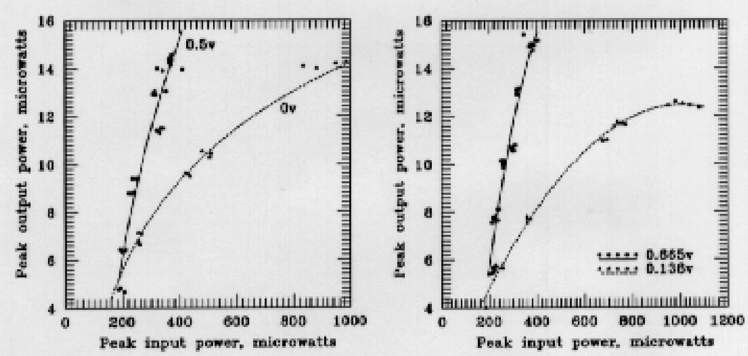


Fig. 8: (a) Measured peak power dependence of the multiplier #2 with bias 0 V and 0.5 V; and (b) with bias 0.136 V and 0.665 V.

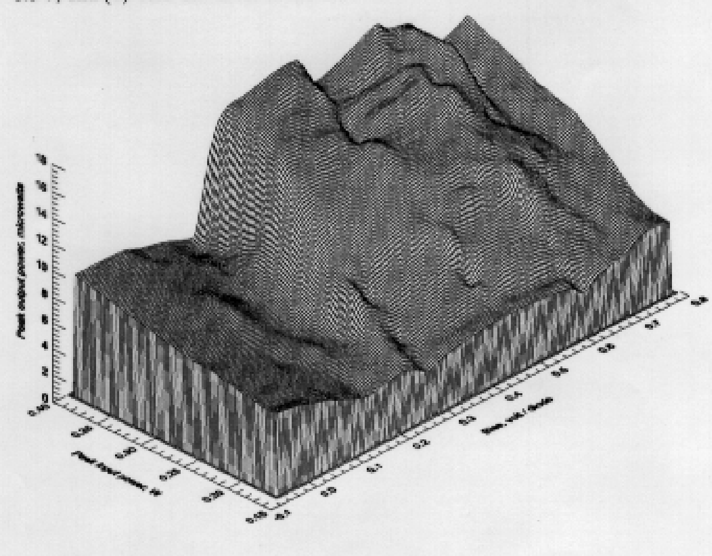


Fig. 9: Measured peak output power as a function of peak input power with different biases from -0.07 V to 0.79 V.

Publications

1.``THz Grid Frequency Doublers,'' J.C. Chiao and D. Rutledge, The 6th International Symposium on Space Terahertz Technology, Pasadena, CA, March 1995. \vskip 0.5cm

Statement of Work

April 1, 1995 -- March 31, 1996

We propose a one-year program to develop second generation of the THz monolithic frequency doubler grids based on Schottky varactor diodes. The goal is to produce a solid-state source with an output power of more than 500µW at 1 THz. Design and testing will be done by the Caltech group, and fabrication by the University of Virginia. Several changes will be done to improve the efficiency:

[1] The polarity of diodes will be corrected to have a proper output power pattern in the far field for multiplier applications.

[2] Biasing tests verify that the frequency multiplication in these diode grids came from varistor multiplication, that is to say, from the nonlinear I-V relationship. The advantage of varistors is that they inherently have real impedances and high cutoff frequency. However, the varactor multiplication relies on variable capacitance, therefore in principle, to be able to have higher doubling efficiency and to handle more power. The plan is to design a coupling-structure metal-pattern array for Schottky varactor diodes which will be designed by Dr. Tom Crowe at University of Virginia to reach higher efficiency.

[3] The key device and system problems then are impedance matching at the fundamental and second harmonic frequencies, and terminating idler frequencies properly when we choose Schottky varactor diodes. More impedance-matching issues will be investigated.

3.0 Receiver Development

3.1 Quasi-optical Slot-Antenna SIS Mixers

PI: Jonas Zmuidzinas
Collaborators: H. G. LeDuc and J. A. Stern (JPL)

Objective:

We are developing low-noise quasi-optical SISmixers for submillimeter wavelengths. Such mixers areneeded in the 400-1200 GHz frequency band for the theFIRST mission. Our mixer is rugged, has a broad fixed-tunedbandwidth of around 200 GHz, is relatively simple tofabricate, and can easily be arrayed. Our goal is toobtain DSB noise temperatures below 10 hf/k across this band.

Progress:

We achieved a major milestone in the first quarter of 1995:we demonstrated a sensitive SIS mixer at 800 GHz.A record sensitivity of 620 K (DSB) was obtained usingan all-niobium twin-slot mixer pumped by our solid-statemultiplied Gunn LO. This is the first demonstration of an 800 GHzSIS mixer whose performance is substantially better (a factor of 5,in our case) than typical corner-reflector cooled Schottky mixersthat have been used extensively at 800 GHz in the past. Our resultis also significantly better (by at least a factor of 2) than wouldbe obtained with an optimized cooled Schottky mixer in a waveguidemount, which could now be built given the recent advances inwaveguide techniques. Our result was reported at the SixthInternational Symposium on Space Terahertz Technology, which washeld at Caltech last March.

Our result 800 GHz result was obtained using a new set of twin-slotdevices recently fabricated at JPL by Rick LeDuc. The design of thesedevices was based on extensive Fourier transform spectrometer (FTS)measurements of previous devices (about 20 devices have been tested).In addition, a substantial effort was invested in developing detailedcomputer models of our circuits. Our earlier measurements (in 1994)showed a very rapid decrease in sensitivity above 700 GHz.Our FTS measurements and modeling led us to the conclusion thatthis was not a fundamental problem, but was mainly due to theroll-off of our tuning circuits, and that significantly betterperformance should be possible with optimized circuits should be possible.The design, mask layout and fabrication, device fabrication, andmixer testing were all performed in the first quarter of 1995.

Planned for next quarter:

Nb devices:
We will continue to characterize the recently fabricated all-Nbslot-antenna mixers using FTS and heterodyne measurements.We hope to improve on our result at 800 GHz, and to pushhigher in frequency. This should be possible since Neal Ericksonat U. Mass. has promised to send us his recently completed750-880 GHz multiplier, which has more output power and awider bandwidth than our source. We will also make FTS measurementson several diagnostic devices which were included on the wafer,in order to verify our choice of material parameters used forthe device simulations.

Al/Nb devices:
We have now convincingly demonstrated that good performance ispossible above 700 GHz with Nb junctions. The next step is todevelop mixers in which the Nb wiring has been replaced by Al,which is a normal metal at 4 K. Because Al has a much lowerresistivity than Nb in its normal state, these devices mayhave better performance than all-Nb devices above 700 GHz.We have recently completed detailed design calculations and the masklayout for these devices. This mask set will include devices designedto operate at 1 THz. The lithography masks are now beingfabricated, and we expect that JPL will be working on thesedevices in the next quarter. Initial mixer tests are expectedby the end of the quarter if the device fabrication goes well at JPL.

3.2 SIS Membrane Waveguide Receiver Development

PI: W. McGrath
Collaborators: M Salez, B. Bumble, J. Stern, H. LeDuc - JPL

Objective:
The objective of this task is two-fold. The first is to develop a novel waveguide mixer design which employs SIS tunnel junctions on thin silicon nitride membranes for operation at 1000-1200 GHz. The 1µm thick SiN membrane will allow waveguide mixer circuits to be extended to at least 1200 GHz by reducing the parasitic effects of thick quartz substrates. The second is to develop new integrated rf circuit designs for niobium nitride (NbN) SIS mixers. NbN-based mixers are expected to operate up to 1400 GHz due to the higher energy gap in NbN. These mixers are being developed for low-background submillimeter wave observational missions such as SOFIA and FIRST as well as ground and balloon-based observatories.

Progress:

- The large-scale model of the membrane mixer was tested without an E-plane tuner. The fixed tuned bandwidth was about 12%. This is very close to the goal of 20%, for this initial result. Additional optimization is required. Modifications are underway to improve the model for broader bandwidth.
- Two batches of NbN junctions with the new rf tuning circuits have been made. The first batch had a magnetic penetration depth much larger than acceptable (nearly 400nm instead of 300nm). The center frequency for the resonant tuning circuit was thus near 400 GHz instead of 630 GHz. The next batch had an acceptable penetration depth and the DC resonant peaks are near 600 GHz; however, the current density was lower than expected, and hence the junction capacitance is larger than anticipated. This batch is currently being tested in the 630 GHz receiver.

Planned for Next Quarter:

- Modify the large scale model: reduce the waveguide height. Measure the bandwidth.
- Test the DC characteristics of new batches of NbN junctions.
- Measure the receiver performance of any accepatable junctions at 630 GHz.

4.0 Backend Electronics

4.1 Digital Autocorrelator Spectrometers (DACS)

PI: Kumar Chandra
Collaborator: J. Zmuidzinas (CIT)

Objective:

The goal of this task is to develop and demonstrate very low power, wide bandwidth digital autocorrelator Spectrometers using VLSI technology for future NASA space missions. A special purpose Application Specific Integrated Circuit (ASIC) will be designed and a prototype low power autocorrelator spectrometer will be built and demonstrated. This development task will produce digital autocorrelator spectrometers with >1000 MHz bandwidth, 1 MHz resolution and <15 Watts of DC power consumption.

In addition to the above task, JPL is also involved in the development of wideband spectrometers using Caltech-developed correlator chips for applications such as future sub-mm wave array telescope. The Caltech correlator chip is designed for use in a parallel architecture to achieve 1 GHz bandwidth. A prototype spectrometer using these chips will be built and tested with the Caltech Submillimeter Telescope (CSO).

JPL is managing two Small Business Innovative Research (SBIR) Phase II contracts todevelop high speed, low DC power correlator chips and high sample rate, low DCpower 2-bitdigitizer using super conductors. The 2-bit digitizers are used with the autocorrelator spectrometers. Such low power, high data rate digitizers can potentially replace some of the frequency down conversion stages in radiometer receivers thus reducing the system DC power consumption.

Digital autocorrelator spectrometers are needed with millimeter and sub-millimeter wave radiometers for spectral analysis of molecular emission lines from interstellar clouds, stellar atmosphere and galaxies and also in the remote sensing of molecules in theEarth's atmosphere for ozone depletion studies. The digital autocorrelator spectrometers will be used in, aircraft and balloon-borne radio telescopes and in space-borne applications. Future astrophysics missions such as FIRST/SMIM and also the remote sensing instruments such as the Microwave LimbSounder in the Earth Observing System (EOS/MLS) will require space qualified digital autocorrelator spectrometers.

Progress:

Spaceborne Inc. under SBIR Phase II contract, has designed and fabricated prototype 64-channel 1-bit correlator chips. The testing of the chips with static input showed that the chip functioned at 500 MHz clock. However, there was cross-talk between the clock and the data inputs (10 dB coupling) which resulted in distortions of the input data. A new packaging is under development to eliminate the coupling and test the chip with dynamic input. The clock distribution circuit has been designed and further simulation will need to be performed to find out clock skew. The module with the high speed 2-bit digitizer and 1:8 Demultiplexor chips has been tested at Caltech The correlator board and the digitizer/demux module have been integrated.

The spectrometer is being being tested.

Planned for the Next Quarter:

- The 1 GHz spectrometer at Caltech will be charecterized
- Work with SBIR Phase II contractor in validating the test results of the 1-bit correlator chip

Schedule:

64-Channel, 500 MHz bandwidth Digital Autocorrelator Spectrometer Development

Tasks	Date	Deliverables
1. PWB design	April, 1995	Chip-on-board design
2. PWB fab.	June, 1995	PWB board
3. Spectrometer assembly	July, 1995	64-channel Spectrometer
4. Testing	Oct, 1995	Test results and report
5. 1-GHz spectrometer	Apr, 1995	Integrate and test CSO spectrometer
Long Term :		
1. Spectrometer	1995-'96	256-Channel spectrometer using SBIR Phase II chips, and Caltech's Mark II correlator chip development
2. Balloon integration	1996-'97	Use JPL-developed spectrometer in Balloon MLS and/or Astrophysics balloon Telescope, Caltech's Mark II correlator spectrometer development
3. Investigate fab. for < 0.5 micron size, 3 volt operation	1997	
4. Design 2-bit correlator chip	1997	
5. Fab. 2-bit correlator chip using < 0.5 micron geometry	1997-'98	
6. Demonstrate 2-bit, low power DACS	1998-'99	

4.2 HEMTS

PI: C. R. Lawrence

Collaborators: P. Smith (MDL)
B. Allen (TRW)
R. Lai (TRW)
D. Streit (TRW)
J. Laskar (Georgia Tech)
P. Lubin (UCSB)
T. Gaier (UCSB)

Objective:

The objective of the work is improved performance---lower noise and greatergain stability---of InP high electron mobility transistors (HEMTs) at cryogenic temperatures. InP HEMTs are the lowest-noise transistors available, and have been extensively developed by industry for room temperature applications.They are the detector of choice for radio astronomy, remote sensing, and deep space communications at frequencies up to about 10^11 Hz. Although their performance improves at low physical temperatures, existing devices have not been optimized for cold operation. Our immediate performance goals are noise less than five times the quantum limit over a 20% bandwidth atfrequencies up to 100 GHz, with a 1/f knee in detected power below 1 Hz, atphysical temperatures less than 20 K. InP HEMTs are enabling technology for proposed transistor-based CBR anisotropy missions such as PSI, and key technology for submillimeter missions such as FIRST and SOFIA, where they are used as IF amplifiers.

The roles of the various participants in the program is as follows:

TRW --- Design and fabrication of wafers; evaluation of devices at room temperature; some design and testing of amplifiers at selected frequencies.
MDL --- E-beam lithography of very short gates on some pieces of wafers; tests of novel passivation structures.
UCSB --- Design, construction, and testing of amplifiers; development of gain stabilization techniques.
G. Tech --- Characterization of transistors on-wafer at cryogenic temperatures, including S-parameters and gain stability.

Progress:

Two lots of four wafers have been processed at TRW. Processing on a third lotoffour wafers is about 80% complete. Four different doping profiles were tried,including one with very high indium content designed for very short gates.Short gates were written at MDL on several wafer pieces.Gain stability measurements at UCSB have shown that the stability of InP HEMTsis similar to that of pseudomorphic HEMTs.

Some sample devices have been measured on-wafer at room temperatures. Results are encouraging. Several wafer pieces have been shipped to Georgia Tech, where measurements on-wafer at cryogenic temperatures will be made.

Amplifiers using new InP transistors in bodies fabricated at UCSB are under construction at TRW; testing at room temperature is expected to begin at TRW this week.

Planned for next quarter:

Characterization of devices produced in the first round of fabrication will be completed.

TRW and MDL will complete fabrication of the third set of four wafers.

Measurements on-wafer and in amplifiers will be used to decide on the most promising design approaches, which will be pursued in a second round of fabrication. The contract for a second round of fabrication has been written and awaits final signatures.

5.0 Planar Array Receiver

PI:	Dr. Philip A. Stimson, JPL
Collaborators:	Dr. Peter H. Siegel, JPL,
	Dr. Henry G. LeDuc, JPL,
	Professor Jonas Zmuidzinas, California Institute of Technology

Purpose:

To develop planar, quasi-optical SIS array receivers operating at submillimeter wavelengths for spectral observations from ground andspace based telescopes.

Planar array receivers offer increased science yield with respect to equivalent single element receivers permitting large area mapping in reduced time and enhanced ground-based observations during the limited period that atmospheric conditions are favorable. Integrated planar array receivers are much simpler than arrays based on waveguide technology, or on multiple planar-element systems, in that all the antennas, mixers and IF removal circuitry is contained on a single wafer. This approach is compatible with integration of IF amplifiers and other system components.

Approach:

A development plan has been formulated which draws on the expertise of Caltech, in very low-noise, high frequency, single element planar receivers, and JPL, where the first planar SIS array receiver has beendemonstrated at 230 GHz. The receiver will use technology from parallel development efforts in digital correlators and integrated IF amplifiers.The device will be tested on the Caltech Submillimeter Observatory in Hawaii in August 1996.

The receiver front-end consists of 7 double slot antenna elements packed in a hexagonal configuration. The feed antennas will illuminate a silicon extended hemispherical lens with built-in antireflection coating. Preliminary calculations of the beam patterns of single elements show excellent off-axis performance with high efficiency and low comatic aberration. The initial frequency of operation will be 690GHz (the CO(6-5) transition), though the design is modular, and the frequency band can be changed simply by using a different SIS chip.Integrated microstrip tuning structures will be used to cancel the SIS junction reactance. Approximately 100 7-element arrays can befabricated on a single wafer, allowing those with the best DC performance to be chosen for RF testing. The 1-4 GHz IF signals will propagate off the wafer in microstrip transmission line and pass intosingle stage integrated indium phosphide HEMT amplifiers located on separate chips in the mixer block. LO power will be provided to thereceiver using commercial Gunn diode and multiplier technology, and injected via a low loss diplexer. Back end processing will be implemented using digital autocorrelators, under development in another parallel effort. The system will be designed on a modular format to allow for future upgrades to larger format arrays.

Progress:(further information available from phil@mihi.jpl.nasa.gov)

We have used our rigorous theoretical model of the array to perform exhaustive calculations of the mutual coupling of the antenna elements on the silicon lens. A report containing the full results of the self and mutual impedance of all the elements has been produced.

The so-called vertical hexagonal configuration has been chosen for the array because it exhibits slightly less cross coupling than the horizontal configuration.

We have analyzed antenna patterns of the receiver front end which have been calculated at the University of Michigan. These indicate that it is preferable to place the receiver elements at an axial position midway between the "elliptical" and "hyperhemispherical" points. The elliptical position suffers from strong off axis gain variation but delivers high gain, while the hyperhemispherical position exhibits low gain and strong off-axis aberrations. A compromise between these provides adequate gain, gain variation, and acceptable side lobe levels.

Planned for Next Quarter:

- Array Cryostat Ordered
- Mask generation started

FY 95 Milestones

• Determination of array element spacing	Feb
• Choice between 2 possible hexagonal configurations	Feb
• Array cryostat ordered	Mar
• Mask design complete	Apr
• Lab test of first fabrication run devices	Sept

B. Earth Observing Systems

B. Earth Observing Systems

B 1. Introduction

To develop sensor technology which will enable the detection and measurement of key molecules, radicals and source gases in the Earth's upper atmosphere. This technology is essential for the successful deployment, on NASA's Chem I Platform, of the Earth Observing System Microwave Limb Sounder, the only instrument capable of detecting and globally monitoring chlorine monoxide and other molecular species, involved in the destruction of the Earth's ozone layer. This technology also enables accurate measurements of the distribution and abundance of other chemical species in the Earth's upper atmosphere as well as on other planets and is generally considered to be on the frontier in opening one of the last remaining untapped regimes of the electromagnetic spectrum.

B 2. Objective

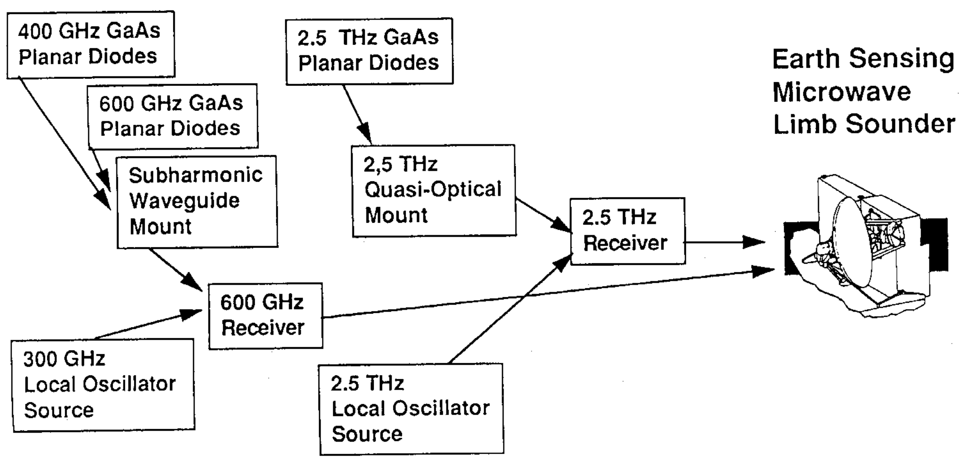
To develop the heterodyne front-end receiver components required for the design, fabrication and deployment of the Earth Observing System Microwave Limb Sounder, its precursor balloon and aircraft experiments and subsequent Earth atmospheric remote sensing instruments. Principle target frequencies for this application include 215 GHz for the measurement of chlorine monoxide and ozone, 315 GHz for the measurement of upper tropospheric water, 640 GHz for the first global measurement of hydrochloric acid and 2522 GHz for the first global measurement of the hydroxyl radical, OH. The technology being funded involves the design, fabrication and testing of low-noise mixers Schottky diode mixers, frequency multipliers, direct millimeter-wave oscillators, MMIC amplifiers and submillimeter wave frequency selective surfaces used to obtain a multiplexing advantage. The task is targeted primarily at advancing and extending the frequency range of specific heterodyne receiver component technology. Goals include the replacement of 1950's based whisker contact diode techniques with state-of-the-art planar integrated diode and circuit technology and the development of novel device structures for use at frequencies where no viable space-based technology currently exists. NASA/JPL has established a unique design and fabrication capability and a strong development team for meeting these objectives and is unique in the country in having all of the elements required, including the science team, in a single location.

B. 3 Work Breakdown Structure (See Figure 2 for road Map)

1. 640 GHZ Mixer (JPL, UVA)
2. 640 GHz Oscillator (JPL, UVA, U. of Mass)
3. OH Radiometer (2.5 THz) Mixers (JPL)
4. 2.5 THz Local Oscillator (MIT-Lincoln Lab)
5. Filterbank Spectrometers

EARTH SENSING SUBMILLIMETER SENSORS ROADMAP

FY94 FY95 FY96 FY97 FY98 FY99 FY00 FY01 FY02



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MAF 9/19/94

Technical Progress

1.0 640 GHz Mixers for Atmospheric Earth Remote Sensing

PI & Task Manager: Dr. Peter H. Siegel, JPL
Co-I's: Dr. Imran Mehdi, Dr. Tracy Lee, Mr. Bob Dengler - JPL
Dr. Tom Crowe - University of Virginia Semiconductor Dev. Lab.

Purpose:
To develop low noise, room temperature, fix-tuned, subharmonically pumped, wide IF bandwidth, planar diode mixers at 640 GHz for the detection of atmospheric ClO, N_2O, HCl and ozone. This technology is essential for meeting the science requirements of the Earth Observing System Microwave Limb Sounder instrument. It also represents an opportunity for the successful deployment of new enabling technology developed under the OACT program, in this case the deployment of a broad IF band planar diode mixer to replace the less reliable, much narrower band whisker contact diode technology found in today's submillimeter wave receivers.

Progress:

Slow but steady progress on all three diode processes is being made. QUID diodes now yielding 2200K SSB at 200 GHz. Discrete diodes now giving record breaking 1450K SSB at 200 GHz. T-anode QUID devices have capacitance below 12fF (best of any devices). Separately biasable diodes now giving 80% yield. 640 GHz diodes in fabrication at both UVa and JPL. InP devices in fabrication at UMich and first batch tested at 200 GHz this quarter. Waveguide mixer blocks under continual test & improvement. Record 17 GHz IF bandwidth achieved with <3500 K SSB in broadband 200 GHz block achieved this quarter. New all-planer quasi-optical subharmonically pumped separately-biased antiparallel-pair-diode mixer design as replacement for waveguide mixer at 640 GHz and potential 2500 GHz unit begun.

Planned for Next Quarter:
Focus shifting to 640 GHz. Delivery of first 640 GHz QUID diodes expected by June. First tests of separately biased diodes expected in April at 200 GHz. Completion of novel all quasi-optic subharmonic mixer expected by end of June.

FY 95 Milestones	O	N	D	J	F	M	A	M	J	J	A	S
Completed 215 GHz QUID diode mixer							**X**					
Completed 640 GHz QUID diode mixer										**X**		
Completed separate bias 215 GHz mixer									**X**			
Completed separately biased 640GHz mixer											**X**	
Completed quasi-optic SHP mixer												**X**

2.0 640 GHz LO for Atmospheric Earth Remote Sensing

PI: Dr. Neal Erickson, University of Massachusetts
Co-I: Dr. Tom Crowe - University of Virginia Semiconductor Device Lab
Task Manager: Dr. Peter H. Siegel - JPL

Purpose:
To develop a solid-state local oscillator source using planar varactor diodes with an output power of 10 mW at 320 GHz.

Progress:

First stage 80-160 GHz doubler completed and now producing a record breaking 40% efficiency and >50mW output power at 160 GHz. Second stage output power now 5 mW at 320 GHz. Second batch 320 GHz devices nearly complete.

Planned for Next Quarter:

Delivery and testing of second batch of planar diodes for 160-320 GHz

FY 95 Milestones	O	N	D	J	F	M	A	M	J	J	A	S
Completed 320 GHz multiplier diodes								**X**				
Completed 320 GHz doubler												**X**

3.0 OH Radiometer

3.1 OH Mixers

PI & Task Manager: Dr. Peter H. Siegel, JPL
Co-I's: Dr. Peter Smith, Dr. Imran Mehdi, Dr. Philip Stimson - JPL
Dr. Jack East - University of Michigan

Purpose:
To develop an all planar heterodyne mixer and low-power solid-state multiplier source for 2500 GHz using GaAs/InP Schottky diodes. The mixer will be required for frequency locking a solid-state laser source planned as a possible local oscillator source for the EOS-MLS OH radiometer. The multiplier source is planned as a baselined local oscillator for the high Tc bolometer mixer to be employed on the EOS-MLS OH radiometer channel.

Progress:

Second round of model measurements completed but unsuccessful due to anisotropy in simulated silicon dielectric material at 20 GHz. Bolometer measurements at 200 GHz on actual lens structure begun as replacement. 200 GHz diodes/antenna mask completed. Diodes in fabrication at UMich and JPL. Second round of theoretical analysis using FDTD completed. Agreement between model measurements and theory excellent for thin slot structures but still shows discrepancy for thick slot design. Further analysis will await bolometer beam patterns (to be completed next quarter). Program shift de-emphasizing Schottky mixer for 2.5 THz caused change of emphasis in design. Lower sensitivity mixer still required for 2.5 THz phase locking of LO source, but new requirement added: 2.5 THz low-power multiplier source. Part of moneys allocated to mixer development now shifted to LO development at 2.5 THz. Revised milestones appear in table below.

Planned for Next Quarter:

200 GHz bolometer beam pattern measurements on mixer structure.
First batch 200 GHz Schottky diode/antenna structures delivered
Initial design of 2500 GHz low-power multiplier completed

FY 95 Milestones	O	N	D	J	F	M	A	M	J	J	A	S
First 2500 GHz planar-diode Schottky mixer												**X**
Completed 2500 GHz multiplier design											**X**	
200 GHz mixer model measurements							**X**			**X**		
Scale model 2500 GHz mult. measurements												**X**

4.0 2.5-THz Solid-State Local Oscillator for the EOS Mission

PI: E. R. Brown
Collaborators: K. Vahala (Caltech), Jonas Zmuidzinas (Caltech), P. Maker (JPL)

Objective:
The goal of this program is to produce an all-solid-state coherent local oscillator for 2.5 THz having an output power of roughly 10 mW. The basis of our approach is a photoconductive mixer (photomixer) made from low-temperature-grown (LTG) GaAs. The photomixer is pumped by two frequency-offset diode lasers.

Progress:

Since the last quarterly report, several experiments have been conducted to reach the stated objectives. First, an all-solid-state 2.5-THz source has been demonstrated using our LTG-GaAs photomixers and two diode lasers containing distributed Bragg reflectors (DBRs). The diode lasers had room-temperature operating wavelengths of approximately 850 and 855 nm, respectively, and were tunable over approximately 1.5 THz in frequency by temperature variation. The photomixer was the same 8x8 micron device developed last quarter. It consisted of submicron interdigitated electrodes mounted at the center of a three-turn log spiral antenna.

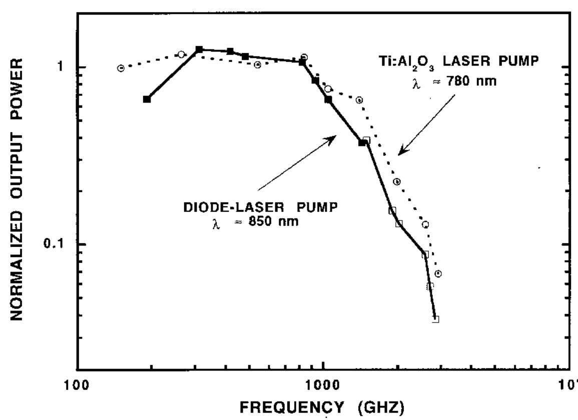
The output power in the range of 1.5 to 3.0 THz is shown in Fig. 1 and is connected to the output power in 0.1-to-1.5-THz range that was measured with DBR diode lasers operating at 850 and 852 nm. Although the output power drops monotonically above 1 THz, the rate of decay is just 6-dB per octave because the photomixer is limited in speed by only one time constant. Therefore, the output power at 2.5 THz is approximately 1 microwatt, compared to about 10 microwatt at the low-frequency end. The absolute power at 2.5 THz was measured at Lincoln Laboratory by a cross-calibrated silicon composite bolometer.

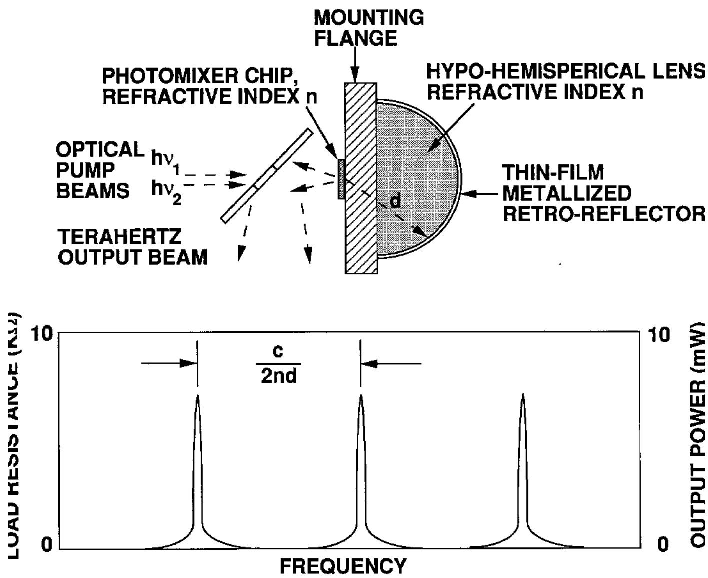
Another area of experimentation has been in resonant output coupling of the photomixer. First, the LTG-GaAs photomixer was coupled to a slot antenna designed for a first resonance at 2.5 THz. Although a resonant peak was seen in the photomixer output, the absolute power was not greater than that of the spiral-antenna photomixer at the same frequency. The reason for this is thought to be ohmic losses in the slot-antenna metallization. The second technique for resonant output was the cavity-coupled photomixer shown in Fig. 2. In this structure, the photomixer chip is mounted on the back side of a hypo-hemispherical silicon lens whose front (spherical) surface is coated with a thin layer of aluminum and gold. In principle, strong standing-wave resonances exist in the cavity formed between the spherical metal mirror and the spiral antenna. At a resonant frequency, an enhanced power should emanate from the spiral antenna into the free space above it. To date, we have confirmed this behavior through a sequence of maxima in the output power from the cavity-coupled photomixer. The absolute power at these maxima is presently being measured.

A final area of progress was the design of a photomixer having better heat dissipation. From previous work, we know that the photomixer performance is greatly limited by degradation of its electrical properties under high optical pump power. This is caused largely by the elevated operating temperature (>> 400 K) . To alleviate the heating problem, we have designed a photomixer incorporating a micro heat sink just below the active layer. The heat sink is a metallized via hole that extends through the entire GaAs substrate to an LTG-AlGaAs etch-stop layer lying just below the LTG-GaAs active layer. To prevent the heat sink from shorting out the photomixer while providing adequate thermal conduction, the thickness of the AlGaAs etch-stop must be at least about 300 nm. The epitaxial growth of the first structure was completed during this quarter, but the fabrication must wait until after 1 April 1995.

Plans for Next Quarter:

- Measure absolute power from hypo-hemispherical cavity-coupled photomixer at 2.5 THz.
- Fabricate heat-sunk spiral-antenna photomixer for operation at 2.5 THz.
- Design distributed LTG-GaAs photomixer for higher-power optical pumping with single-frequency master-oscillator power-amplifier (MOPA) diode laser.
- Send 2.5 THz photomixer to Caltech for pump tests with 0.5-W MOPA diode lasers.




MOUNTING
FLANGE
PHOTOMIXER CHIP,
REFRACTIVE INDEX n
HYPO-HEMISPERICAL LENS
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PUMP
BEAMS
hν1
hν2
d
THIN-FILM
METALLIZED
RETRO-REFLECTOR
TERAHERTZ
OUTPUT BEAM
10
0
c
2nd
10
0
OUTPUT POWER (mW)
FREQUENCY

5.0 Filterbank Spectrometers

PI: Kumar Chandra

Objective

The goal of this task is to design, fabricate and test 25 filterbank spectrometers for the EOS-MLS. This task is responsible from the brass-board implementation to flight model. The specifications for the filterbanks are that each filterbank consumes 6 watts of DC power, has a mass of 5 kg and has small size. The spectrometer will be qualified for space environment.

Progress

- Screening requirements for the filterbank components have been sent to various vendors.
- Vendor survey for Master oscillator and 2nd local oscillators was done and cost estimates have been received.
- Discussions with industry to fabricate filterbank spectrometers and 2nd LO and down conversion.

Plans for Next Quarter

- Continue to work on the design of filterbank and 2nd LO.
- Packaging issues will be reviewed to reduce the size and mass.